Throughput Analysis of the IEEE 802.11p Enhanced Distributed Channel Access Function in Vehicular Environment

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Abstract

This paper proposes an analytical model for the throughput of the Enhanced Distributed Channel Access (EDCA) mechanism in IEEE 802.11p MAC sub-layer. Features in EDCA such as different Contention Windows (CW) and Arbitration Interframe Space (AIFS) for each Access Category (AC), and internal collisions are taken into account. The analytical model is suitable for both basic access and the Request-To-Send/Clear-To-Send (RTS/CTS) access mode. The proposed analytical model is validated against simulation results to demonstrate its accuracy.

I. Introduction

Modern Intelligent Transportation Systems (ITS) aim to apply Information and Communication Technologies (ICT) in order to improve quality, effectiveness, and safety of future transportation systems [1]-[2]. It is envisioned that the deployment of advanced ITS technologies will contribute to effective management of traffic in urban areas as well as improvement of safety on highways and roads. In addition, access to broadband Internet via ITS technologies will enable a variety of entertainment applications that are expected to revolutionize the quality of experience for the passengers in long haul journeys. Vehicle to Vehicle (V2V), alternatively known as Car to Car (C2C) or Inter-Vehicle Communications (IVC), combined with Vehicle to Infrastructure (V2I) communications, also know as Roadside to Vehicle Communications (RVC), are two key enabling components of ITS technologies. V2V relys on direct communications between individual vehicles, while V2I relys only on communications facilities among vehicles and fixed roadside infrastructures.

Due to the characteristics of propagation environment, and the requirements of the specific applications in VANETs, the IEEE 802.11p has been proposed for Wireless Access in Vehicular Environments (WAVE) [7]. The IEEE 802.11p uses an EDCA MAC sub-layer protocol designed based on that of the IEEE 802.11e with some modifications; while the physical layer is similar to that of the IEEE 802.11a standard. The IEEE 802.11p aims to provide both V2V and V2I communications in ranges up to 1000 m that could function in relative velocities up to 30 m/s, and in a variety of environments (e.g., urban, suburban, rural and motorway). The IEEE 802.11p could support transmission rates from 3 to 27 Mb/s (payload) over a bandwidth of 10 MHz which is half of the bandwidth in 802.11a.

Performance analysis of the IEEE 802.11p MAC sub-layer is an important and challenging problem that has been partially investigated in some recent publications. In [3] and [4] simulation based studies of the performance of the IEEE 802.11p MAC sub-layer are given. These papers provide measurements of the aggregate throughput, the average delay, and the packet loss due to collision in some specific simulation scenarios.

There are also some recent works on the analytical modelling of the MAC sub-layer of the IEEE 802.11e, based on the original model proposed by Bianchi [8] for the saturated throughput of the IEEE 802.11 [5] Distributed Coordination Function (DCF) mode under an ideal channel condition. An extended model based on [8] to capture the main features of EDCA is proposed in [11]. Virtual collisions among different ACs inside a station with AIFS values for different ACs are considered in this work. However, the calculation of transmission probability results great complexity. In [12], an analytical model is presented incorporating an accurate CW and AIFS differentiation. However, the model assumes that each station only has one AC, so the effect of virtual collisions is neglected. In [9], an analytical model for the saturated throughput of the EDCA mode of the IEEE 802.11e MAC sub-layer is given. However, the model does not take virtual collision into consideration while calculating the probability for contention zones. Following the model in [9], a two-dimensional Markov chain model is proposed in [10] to analyse EDCA in a saturated scenario for 802.11e. The model considers different AIFS and CW values for different priority queues; in addition, the virtual collisions for different priority queues inside the same stations are taken into account in these models. However, the calculation of transmission probability for each AC is not accurate due to the different contention windows defined in IEEE 802.11e. None of the aforementioned existing analytical models are suitable and accurate enough for the IEEE 802.11p standard.

This paper presents an analytical model for the EDCA mechanism in the 802.11p MAC sub-layer. The proposed model extends the Markov chain analysis in [8], considering the accurate specifications of 802.11p standard. First, a two-dimensional Markov chain is generated in this paper to model the backoff procedure for each AC queue. Different CW and AIFS values for each AC are taken into account. Then, slots are divided into different zones for deriving the relation between the transmission probability and the collision probability. The collision probability for each AC is derived taking internal collisions into consideration. Finally, an accurate model for the throughput of each AC is derived. Both basic and RTS/CTS access modes are supported in the proposed model. The proposed model is validated against simulation results to demonstrate its accuracy.

The rest of the paper is organized as follows. In Section II, the analytical model for the throughput of EDCA in the IEEE 802.11p MAC sub-layer is proposed. Section III validates the accuracy of the proposed model by comparing the analytical results with those obtainned by means of simulations. The summary and the concluding remarks are given in Section IV.

II. Analytical model

In this section, a two-dimensional Markov chain is used to model the backoff procedure for each AC queue. First, we obtain the transmission probability of each AC queue by analyzing the Markov chain. With the consideration of internal collision, slots are divided into different zones. Then, the collision probability of each AC queue is represented by transmission probability. The transmission probability for each AC is obtained. Finally, an accurate model for the throughput of each AC is derived. Both basic and RTS/CTS access modes are taken into account in the proposed model.

In the proposed analytical model in this paper, AIFS, CW for different ACs, and the internal collisions inside each station are taken into account. AC0 is the traffic flow with the highest priority, i.e., AC_VO, and AC3 is with the lowest priority, i.e., AC_BK. The analytical model is based on Markov chain analysis in [8]. A saturated scenario is considered, where the active

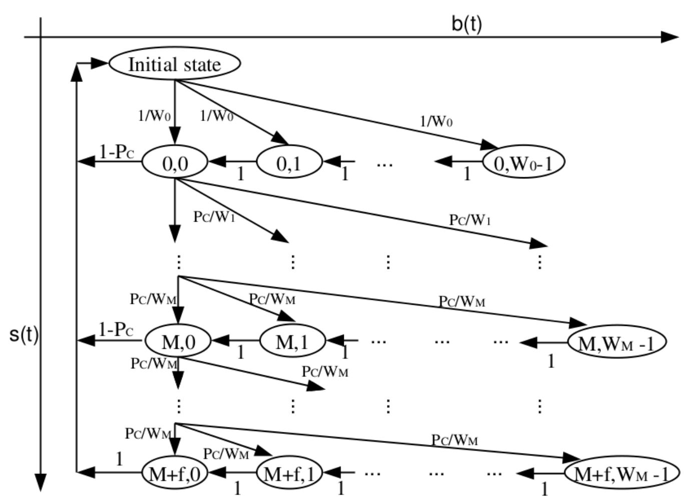

Fig. 1. Two-dimensional Markov chain for a single AC

ACs will always have backlogged packets waiting for transmission. The aim is to analyze the performance of MAC sub-layer; thus, without loss of generality, the packet losses due to the channel errors are excluded.

The basic model in [8], which is still valid for each AC, is further extended in this paper as follows. The two-dimensional Markov chain representing the dynamic behavior of the EDCA backoff process for an individual AC is shown in Fig. 1. The state $(s(t), b(t))$ is defined as follows: $s(t)$ is the backoff stage of a Head-Of-Line (HOL) packet for each AC at time t, defined as the number of collisions that the HOL packet has suffered up to time t, while $b(t)$ is the backoff counter at time t. The packet is sent whenever the backoff counter becomes zero regardless of the backoff stage. The model starts from an initial state which is returned to after a successful transmission or a packet dropping event after exceeding the retry limit at stage $M + f$.

The transition probabilities in the Markov chain in Fig. 1 are given in the following.

$$\begin{array}{l} P(i,k|i,k+1) = 1, \text{for } 0 \le k \le W_i - 2,\ 0 \le i \le M+f \\ P(\text{Initial state}|i,0) = 1 - P_C, \text{for } 0 \le i \le M+f-1 \\ P(0,k|\text{Initial state}) = 1/W_0,\ \text{ for } 0 \le k \le W_0 - 1 \\ P(i,k|i-1,0) = P_C/W_i, \text{for } 0 \le k \le W_i - 1,\ 1 \le i \le M+f \\ P(\text{Initial state}|M+f,0) = 1, \text{for } 0 \le k \le W_0 - 1, \end{array} \quad (1)$$

where M is the maximum number of times the contention window may be increased, P_C is the collision probability, and $M + f$ is the maximum number of trails before dropping a frame. $(W_0 - 1)$ is the backoff window size at stage 0, which is equal to CW_{min}. $(W_i - 1)$ represents the backoff window size at stage i. Since the maximum window size at stage i, namely CW_i, is given by

$$CW_i = \begin{cases} CW_{min}, & \text{for } i = 0 \\ 2 \cdot (CW_{i-1} + 1) - 1, & \text{for } 1 \leq i \leq M - 1 \\ CW_{max}, & \text{for } M \leq i \leq M + f \end{cases} \quad (2)$$

The first line in (1) accounts for the fact that, at the beginning of each slot time, the backoff counter is decreased by one. The second line in (1) corresponds to the case when the old frame has been successfully transmitted, and a new frame is about to be transmitted. Thus, the process moves back to the initial state. The third line in (1) states the process randomly proceeds to one of the states in stage 0 from the initial state when the transmission of a new frame starts, and the backoff counter is reset to a random value, b(t), between 0 and $(W_0 - 1)$. The fourth line in (1) describes when an unsuccessful transmission occurs at backoff stage $(i-1)$. In this case, the process moves to the next backoff stage, and the new backoff value is randomly chosen from interval $[0, W_i - 1]$. After stage M, W_i is not increased beyond $W_M = CW_{max} + 1$. The last line in (1) states that once the backoff stage reaches the retry limit of $M + f$, the frame is discarded if the transmission is not successful. In this case, the next HOL data frame will be set for transmission. Thus, the process transits to the initial state with probability of one.

Now, we analyze the Markov chain in Fig. 1, to obtain transmission probability for each AC queue in any given time slot. Let $b_{i,k}$ be the stationary probability of state (s(t)=i, b(t)=k) in the Markov chain, which is defined as:

$$\begin{aligned} & b_{i,k} \triangleq \lim_{t\to\infty} P(s(t) = i, b(t) = k), \\ & \text{for } 0 \leq i \leq M + f,\ 0 \leq k \leq W_i - 1. \end{aligned} \quad (3)$$

From the transition probabilities in (1),

$$b_{i,0} = (P_C)^i \cdot b_{0,0},\ \text{for } 0 \leq i \leq M + f. \quad (4)$$

From the first line in (1), state $(i, k + 1)$ goes to (i, k) with probability of one. For any state at stage 0,

$$b_{0,k} = \sum_{K=k}^{W_0-1} P(0, K) = \frac{W_0 - k}{W_0} \cdot (1 - P_C) \cdot \sum_{i=0}^{M+f} b_{i,0}. \quad (5)$$

For any state at other stages, (i.e., $(i, k), 1 \leq i \leq M + f, 0 \leq k \leq W_i - 1$),

$$b_{i,k} = \sum_{K=k}^{W_i-1} P(i, K) = \frac{W_i - k}{W_i} \cdot P_C \cdot b_{i-1,0}. \quad (6)$$

Given that

$$\sum_{i=0}^{M+f} b_{i,0} = \frac{b_{0,0}}{1 - P_C}, \quad (7)$$

By (4), (5), (6) and (7),

$$b_{i,k} = \frac{W_i - k}{W_i} \cdot b_{i,0},\ \text{for } 0 \leq i \leq M + f,\ 0 \leq k \leq W_i - 1. \quad (8)$$

Since a transmission occurs whenever the backoff counter becomes zero, the transmission probability for an AC can be expressed by

$$\tau = \sum_{i=0}^{M+f} b_{i,0} = \frac{b_{0,0}}{1 - P_C}. \quad (9)$$

Since the sum of all states in the Markov chain is equal to one, $\sum_{i=0}^{M+f} \sum_{k=0}^{W_i-1} b_{i,k} = 1$,

$$\tau = 2(1 - P_C)[\frac{1}{1 - P_C} + W_0 \sum_{i=0}^{M} (2P_C)^i + W_M \sum_{i=M+1}^{M+f} (P_C)^i]^{-1} \quad (10)$$

Note that for each AC, W_0 and W_M are different, which results in different transmission probability formation for different ACs.

Now we just need to find another equation that includes both τ and P_C to compute the transmission probability. Two features make 802.11p different from 802.11 on the collision probability. One is the different AIFSs for different ACs; the other is the internal collision inside a single station. Since the higher prioritized traffic has a shorter AIFS, it may try to transmit even before the lower prioritized traffic finishes the waiting for its own longer AIFS. Slots could be divided into different contention zones for different ACs. As an example, Fig. 2 shows the contention zones used for a higher priority $AC\alpha$ and a lower priority

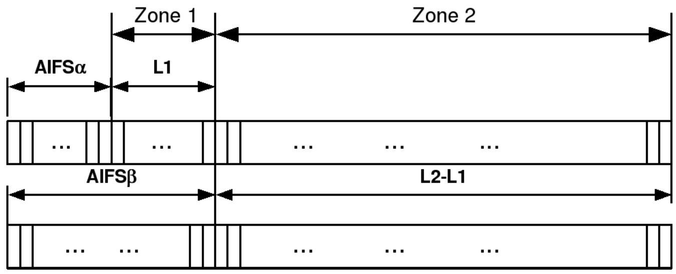

Fig. 2. Contention zones.

$AC\beta$. L_1 is the number of slots that AIFS[α] is shorter than that of AIFS[β], $L_2 = min(W_M[AC])$. Once the backoff timers in more than one EDCAF become zero, either an internal or an external collision happens. The internal collisions are resolved by a scheduler that grants the current TXOP to the AC queue with the highest priority. Thus, these collisions will not waste channel resources. Obviously, this is not the case for the external collisions. Each station has the same priority like the DCF of the IEEE 802.11 standard. Hence, external collisions are possible and will waste some of the shared the channel resources. The internal collisions occur in Zone 2 only while external collisions may occur in both zones. In Zone 1, only $AC\alpha$ participate in contentions, while both ACs contend for the channel in Zone 2.

We use another Markov chain to model the transition of slots, so as to calculate the stationary probability for the slot in each zone. Fig. 3 shows the Markov chain for all the slots in both contention zones. p_i denotes the probability that no station

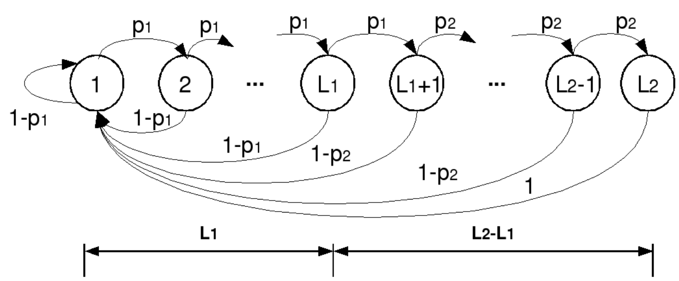

Fig. 3. Markov chain for slots in both contention zones.

transmits in Zone i in a SlotTime. Suppose there are N nodes that each has two AC queues and always have a packet to transmit.

$$\begin{cases} p_1 = (1-\tau_\alpha)^N \\ p_2 = (1-\tau_\alpha)^N(1-\tau_\beta)^N \end{cases} \tag{11}$$

Let t_i be the stationary probability of state i in the Markov chain, which is defined as:

$$t_i \triangleq \lim_{t\to\infty} P(i), \text{for } 1 \le i \le L_2. \tag{12}$$

From the transition probabilities in Fig. 3,

$$t_i = \begin{cases} t_1 \cdot (p_1)^{i-1}, \text{ for } 1 \le i \le L_1 + 1 \\ t_1 \cdot (p_1)^{L_1} \cdot (p_2)^{i-L_1}, \text{ for } L_1 + 2 \le i \le L_2. \end{cases} \tag{13}$$

Since the sum of all states in this Markov chain is equal to one, $\sum_{i=1}^{L_2} t_i = 1$. Hence,

$$t_1 = (\frac{1-(p_1)^{L1+1}}{1-p_1} + (p_1)^{L_1} p_2 \frac{1-(p_2)^{L_2-L1-1}}{1-p_2})^{-1} \tag{14}$$

Therefore, the stationary distribution Z_i for each zone can be calculated as follows.

$$\begin{cases} Z_1 = \sum_{i=1}^{L_1} t_i \\ Z_2 = \sum_{i=L_1+1}^{L_2} t_i \end{cases} \tag{15}$$

The collision probability experienced by each AC is calculated this way. Let $P_{C_{ACi}}$ denote the collision probability of each AC in Zone i. Note $AC\beta$ does not transmit any packet in Zone 1, $P_{C_\beta 1}$ is 0.

$$\begin{cases} P_{C_\alpha} = Z_1 P_{C_\alpha 1} + Z_2 P_{C_\alpha 2} \\ P_{C_\beta} = P_{C_\beta 2} \end{cases} \tag{16}$$

Since only higher prioritized AC transmits in Zone 1, the collisions for $AC\alpha$ in Zone 1 are pure external collisions.

$$P_{C_\alpha 1} = 1 - (1-\tau_\alpha)^{N-1} \tag{17}$$

In Zone 2, the high prioritized AC only collide with packet from other stations, while the lower prioritized AC collides with transmission both from other stations and the higher prioritized AC in the same station. Thus,

$$\begin{cases} P_{C_\alpha 2} = 1 - (1-\tau_\alpha)^{N-1}(1-\tau_\beta)^{N-1} \\ P_{C_\beta 2} = 1 - (1-\tau_\alpha)^{N}(1-\tau_\beta)^{N-1} \end{cases} \tag{18}$$

Till now we have another equation that indicates the relation between τ and P_C. The τ_i could be solved using the above equations. With the obtained transmission probability, we are about to calculate the throughput of each AC. Let $P_{tr_{AC}}$ be the probability that at least one transmission exists in a slot time for one AC, $P_{S_{ACi}}$ be the probability that a successful transmission over the shared channel in a given time slot for a specific AC in Zone i.

$$\begin{cases} P_{tr_\alpha} = 1 - (1-\tau_\alpha)^N \\ P_{tr_\beta} = 1 - (1-\tau_\beta)^N \end{cases} \tag{19}$$

$$\begin{cases} P_{S_\alpha 1} = \frac{N\tau_\alpha(1-\tau_\alpha)^{N-1}}{P_{tr_\alpha}} \\ P_{S_\alpha 2} = \frac{N\tau_\alpha(1-\tau_\alpha)^{N-1}(1-\tau_\beta)^N}{P_{tr_\alpha}} \\ P_{S_\beta 1} = 0 \\ P_{S_\beta 2} = \frac{N\tau_\beta(1-\tau_\alpha)^{N}(1-\tau_\beta)^{N-1}}{P_{tr_\beta}} \end{cases} \tag{20}$$

The channel idle probability for a slot in each zone can be calculated as following.

$$\begin{cases} P_{i1} = (1-\tau_\alpha)^N \\ P_{i2} = (1-\tau_\alpha)^N(1-\tau_\beta)^N \end{cases} \tag{21}$$

Let S denote the average throughput of a single station in the system. Thus,

$$S = \frac{E[payload\ transmitted\ in\ a\ SlotTime]}{E[length\ of\ a\ SlotTime]} \tag{22}$$

If we denote the average packet size by L, the numerator of (22) S_α can be given by $P_{tr_\alpha}(Z_1 P_{S_\alpha 1} + Z_2 P_{S_\alpha 2})L$, while for $AC\beta$, the numerator of S_β is $Z_2 P_{tr_\beta} P_{S_\beta 2} L$. The denominator of (22) can be obtained as follows. Let len_i denote the average length of a slot time in Zone i.

$$\begin{cases} len_1 = [P_{i1} \times aSlotTime] + [P_{tr_\alpha} P_{S_\alpha 1} TS_\alpha] + [P_{tr_\alpha}(1-P_{S_\alpha 1})TC_\alpha] \\ len_2 = [P_{i2} \times aSlotTime] + [P_{tr_\alpha} P_{S_\alpha 2} TS_\alpha + P_{tr_\beta} P_{S_\beta 2} TS_\beta] + [(1 - P_{i2} - P_{tr_\alpha} P_{S_\alpha 2} - P_{tr_\beta} P_{S_\beta 2})TC_\alpha] \end{cases} \tag{23}$$

$$E[length\ of\ a\ SlotTime] = Z_1 len_1 + Z_2 len_2 \tag{24}$$

The first term in (23) accounts for the idle time slots; the second term corresponds to the successful transmissions; and the third term represents the collisions. TS_i is the average time the channel is sensed busy because of a successful transmission of AC_i, and TC_i is the average time the channel is sensed busy by each AC_i. The expressions TS_i and TC_i for AC_i in the basic access mode can be derived as follows:

$$\begin{aligned} TS_i &= T_H + T_{L_i} + T_{SIFS} + \delta + T_{ACK} + T_{AIFS_i} + \delta \\ TC_i &= T_H + T_{L_i^*} + T_{AIFS_i} + \delta, \end{aligned} \tag{25}$$

where T_H is the transmission time periods of the frame header; T_{SIFS} and T_{AIFS_i} are the SIFS and AIFS periods for AC_i, respectively. T_{ACK} is the ACK transmission time; T_{L_i} is the transmission time of the average payload for AC_i; $T_{L_i^*}$ is the transmission time of the largest payload involved in a collision, and δ is the propagation delay. For the RTS/CTS access mode,

$$\begin{aligned} TS_i &= T_{RTS} + T_{SIFS} + \delta + T_{CTS} + T_{SIFS} + \delta + T_H \\ &\quad + T_{L_i} + T_{SIFS} + \delta + T_{ACK} + T_{AIFS_i} + \delta \\ TC_i &= T_{RTS} + T_{AIFS_i} + \delta. \end{aligned} \tag{26}$$

Hence, the average throughput for each AC can be given by (27).

$$\begin{cases} S_\alpha = \dfrac{P_{tr_\alpha}(Z_1 P_{S_\alpha 1} + Z_2 P_{S_\alpha 2})L}{Z_1 len_1 + Z_2 len_2} \\ S_\beta = \dfrac{Z_2 P_{tr_\beta} P_{S_\beta 2} L}{Z_1 len_1 + Z_2 len_2} \end{cases} \tag{27}$$

As it can be seen from (27), although RTS/CTS assists to avoid the hidden problem, the overhead caused by the acknowledgement and handshakes reduce the performance of systems with high mobility like vehicular networks. RTS/CTS access mode exhibits superior efficiency in low relative velocity and basic access mode appears better efficiency than RTS/CTS in high relative velocity [13].

III. Simulation Results

In this section, we use simulation results to validate the accuracy of the proposed analytical model. We use the well-known simulation tool, NS-2 [14], from Lawrence Berkeley National Laboratory and the implementation of 802.11e EDCA [15] in NS-2 from the TKN group in Technical University of Berlin. Some part of the original simulation codes have been changed according to the draft standard IEEE 802.11p [7] in our work.

The simulations in this section are implemented in such a scenario that helps the system to achieve steady performance disregarding the effect from the fast movement of vehicles. One Road Side Unit is place in the middle of the reference area, surrounded by different numbers of nodes in each simulation. The nodes are placed in a circle keeping the same distance to the RSU. Each node is equipped with two ACs. The interval of packet arrival is 1 ms, so that each AC queue is assured with saturated traffic load. All nodes try to send packets to the RSU. The communication range of the nodes are set to be 1 km according to IEEE 802.11p standard. The rest of the major simulation parameters are chosen from the latest draft IEEE 802.11p standard as listed in Table. I.

TABLE I
Parameter setting

Packet payload	683 μs 512 bytes @ 6 Mb/s
PHY header	64 μs 192 bits @ 3 Mb/s
MAC header	43 μs 256 bits @ 6 Mb/s
ACK	101 μs 192 bits + 14 bytes @ 3 Mb/s
Slot time	13 μs
SIFS	32 μs
DIFS	58 μs
δ	2 μs
CW_{min}	15 slots
CW_{max}	1023 slots
TS_i	Header+Payload+SIFS+δ+ACK+$AIFS_i$+δ
TC_i	Header+Payload+$AIFS_i$+δ

The first observation in Fig. 4 is that the results from the analytical model matches those of the simulations. The normalised measured throughput is calculated by dividing the absolute throughput by the channel capacity. As the number of vehicles increases, throughput decreases due to collisions among the stations. AC2 shows absolute priority comparing with AC3. Although they have the similar contention window size, different AIFSs assure the priority of higher prioritized traffic. Due to the lack of pages, service differentiation analysis and system performance in vehicular environment will be discussed based on simulation results in our future work.

IV. Conclusion

We introduce a novel Markov chain model for IEEE 802.11p, taking AIFS, CW for different ACs, and the internal collisions inside each station into account. The analytical model is used to investigate the performance of the IEEE 802.11p MAC sub-layer in terms of throughput. The proposed model is validated for its accuracy by simulations in this paper. All of the analyses and simulations in this paper are performed under the assumptions of ideal channel conditions, saturation traffic, and a single-hop heterogeneous traffic network environment. Further study on the performance analysis of 802.11p could be followed.

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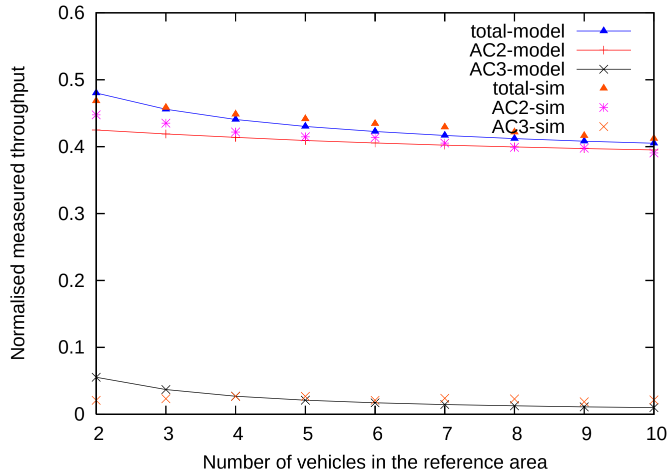

Fig. 4. Normalised throughput versus the number of vehicles in the reference area.

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